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STUDIES FOR STUDENTS

A CLASSIFICATION OF BRECCIAS

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Few geologic structures so lend themselves to diverse interpretations as the beds of broken rock called breccia. Example after example might be cited of breccias of Europe and America which have been differently explained by different students during the last half-century and as to whose origin no consensus is yet attained. This diversity of opinion seems partly due to the large number of processes by which rocks are broken up, assembled, and cemented into breccia, and to the fact that breccias may offer no very obvious and indisputable evidences of the method of their making. Diagnosis generally requires the use of multiple working hypotheses and may proceed chiefly by the process of elimination. For this reason a genetic classification which the writer has prepared in connection with a field study of certain breccias affecting the Wapsipinicon stage of the Devonian of Iowa may prove of interest to students of these structures.

The diagnosis of a breccia requires the close observation of its most intimate characteristics as well as of its associations with the adjacent rocks. The matrix may be like or unlike the fragments lithologically. It may be a chemical precipitate, a sedimentary deposit, or the detritus of attrition. In volume it may be greater or less than the fragments—interstitial, merely filling the spaces between the fragments closely packed, or preponderant, forming the larger part of the rock-mass in which the fragments are sporadic.

The fragments may be of any size, from huge blocks down to chipstone. Lithologically they may be similar or dissimilar, according as they result from the fragmentation of a homogeneous rock-mass or from that of heterogeneous beds. They may be sharply angular, more or less rounded by attrition in earth movements, or even in part water-worn and approaching a conglomerate.

They may be local in derivation, produced by the breaking up *in situ* of a terrane, or they may have suffered transportation from distant sources. They may be simple or of complex and brecciated structure, the result of an earlier brecciation.

Breccia may form a mass entirely destitute of planes of bedding. When bedded in a distinct stratum it may be classified as *endostratic*.

A *crackle breccia*, representing incipient brecciation, is one whose fragments are parted by planes of fission and have suffered little or no relative displacement. The fragments match along their apposed sides. The matrix is confined to the seams and is commonly a chemical deposit.

A *mosaic breccia* is one whose fragments have been largely but not wholly disjointed and displaced. The system of continuous cracks of the crackle breccia has been destroyed, but more or less of the fragments still match along adjacent surfaces and show that they are consanguineous parts of once unbroken laminae or larger beds. The term suggested is not a happy one, yet these breccias may recall some ill-preserved mosaics of ancient ruins. The matrix is confined to the seams and to the wider and irregularly shaped interstices.

A *rubble breccia* is one in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch.

A *breccia of sporadic fragments* is one in which the fragments are imbedded in a preponderant matrix like plums in a pudding. It recalls the term "plum-cake rock," applied by the quarrymen of North England to the breccias of their region. In his study of the Permian Midland breccias of England, King[1] distinguishes an endostratic breccia of this class by terming it "breccia sandstone," thus emphasizing the bedded matrix rock.

Breccia may be fossiliferous. Fossils may be restricted to the fragments or to the matrix or may be found in both. Fossils of the matrix may themselves be fragments. Brecciation may be practically contemporaneous with the involved deposits. Such are the *intraformational breccias* of Walcott. In certain classes of breccia the matrix is of the same age as the fragments. In other classes it is younger, and in still others it may even be supplied by an older bed.

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[1] W. W. King, "Permian Conglomerates of the Lower Severn Basin," *Quar. Jour. Geol. Soc. London*, LV (1899), 105.

Breccia may be of slight extent and evidently due to local causes. On the other hand, some of the most perplexing breccias are regional and demand causes equally widespread in operation.

According to the conditions under which they accumulate, breccias may be classified as *subaërial*, *subaqueous*, or *endolithic*, formed within the lithosphere, the earth's crust.

In classifying breccias genetically it will be remembered that the making of a breccia involves, or may involve, three distinct processes—fragmentation, assemblage of the fragments, and cementation by the introduction of the matrix. In any given breccia all of these processes may belong to the same or to different categories. The genetic classification may have in view either fragmentation, as in crush breccias, or assemblage, as in several other types.

Subaërial breccias, in which both fragmentation and assemblage are above ground, may be classified as follows:

Residual breccia
Talus breccia
Rock-glacier breccia
Landslide breccia
Bajada breccia
Glacial breccia
Volcanic breccia

Residual breccia.—This type is formed of the angular débris of the waste mantle. It has been designated as "basal breccia,"[1] since it corresponds in position to a basal conglomerate. But all subaërial breccias covered and preserved by the deposits of a transgressing sea may correspond equally well to basal conglomerates, so that some designation seems preferable which suggests the residual origin of this specific kind.

Residual breccias develop especially on Karst topographies where the limestone of the country rock contains cherty beds. Under long denudation the surface with its characteristic sink-holes and closed valleys comes to be covered in places to some depth with breccia of sharp-edged chips of flint, and this by submergence may be incorporated into the sequence of the geologic formations.

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[1] W. S. Smith and C. E. Siebenthal, *U.S. Geol. Surv.*, *Geol. Atlas*, Joplin Folio (148), p. 9.

The residual breccia of the Joplin district of Missouri has been described by Winslow,[1] Smith and Siebenthal,[2] and others. The breccia-producing rocks are Mississippian limestones rich in chert. At the close of the Mississippian the region was uplifted and, under long subaërial erosion, developed a typical Karst topography mantled with angular cherty waste. During early Pennsylvanian times the area was deeply submerged; the Carboniferous sea transgressed, but without either leveling the relief or assembling and rounding the residual cherts. The matrix is largely supplied by the sea-clays of the Cherokee formation. The residual breccia thus formed suffered further changes. Solution of the underlying limestone has caused the breccia to founder, producing complex brecciation and intermingling blocks of the country rock. Groundwater has also introduced a matrix of lead and zinc ores and jasperoid silica.

Talus breccia.—Accumulating at the foot of cliffs, from fragments broken off by frost and temperature changes, talus breccia is a rubble of sharp-edged fragments, wedge-shaped in radial section, and quite devoid of bedding. Stratification may be rudely simulated, since slabs and other unequiaxed blocks creeping and sliding down the slope come to rest with their longer axes parallel with the surface. Owing to greater inertia, the larger blocks may gather at the base. Small fragments prevail, but blocks of some considerable size may be supplied by local sapping. The matrix (the finer material derived from the weathering of the cliff and of the talus) is interstitial and lithologically identical with the fragments. Some of the matrix, however, may be foreign—dust and sand brought in by wind, humus of a soil cover, and travertine deposited by springs issuing from the cliff's base.

Talus breccias are local and extremely limited in width. Even under an arid climate favoring the perpetuation of cliffs, even in the hamada desert, where long lines of marching cliffs form the high risers for the broad steps of rock plateaus, talus accumulations are rapidly consumed by deflation and are but a few rods wide. The material is local and there is no zonal arrangement of fragments of different lithologic kinds.

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[1] Arthur Winslow, *Missouri Geol. Surv.*, VII (1894), 464 f.

[2] *Op. cit.*, p. 9.

An example of a talus breccia is described by Wilson[1] as occurring at the base of a cliff of Keweenawan sandstones covered by a sheet of ancient diabase.

Rock-glacier breccia.—A subspecies of talus breccia is that produced by rock glaciers, talus glaciers, or rock-streams, as they are variously known.[2] Talus may be very rapidly produced where the wedgework of frost is especially efficient, as in cold climates, on the lofty walls of cirques composed of rock that favors fragmentation by close jointing, or other structures. Under the urge of its own weight and that of the expansion of interstitial ice talus creeps forward from the feeding cliff in long tongues of waste which in shape somewhat resemble glaciers. Rock-glacier breccia differs from talus breccia only in its greater extension normal to the cliff, in the movement of the material to greater distances and with very gentle slopes, and in the fact that unequiaxed blocks may be expected to be found set at all angles, owing to the movement of material *en masse.*

The famous limestone breccias of Gibraltar, described by Ramsay and Geikie,[3] are attributed to this class. These breccias occupy wide tracts about the base of the Rock of Gibraltar and reach a thickness of at least 100 feet. Their slope in places does not exceed two or three degrees. The fragments are almost invariably quite angular. They vary in size from grit up to blocks 12 feet or more in diameter, and are distributed without regard to size and shape. They are no larger at the base of the cliffs than on the outskirts of the formation. The matrix is earthy and cements the breccia into firm rock. The authors cited attribute fragmentation to the work of frost under far severer climatic conditions than now obtain. The assemblage of the breccia by gravity in ordinary talus is negatived by the extent and slope and apparently by the set of the fragments. The angularity of the fragments, their size, and their lack of sorting preclude the theory of transportation by torrential streams upon detrital slopes. It is concluded that heavy trains of débris saturated by meltings of thick snows have moved *en masse* down the steep slopes and out over the lower grounds below. The junior author reaffirmed this theory in 1881 and compared the breccia directly with the talus glaciers of the Rocky Mountains.[1]

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[1] A. W. G. Wilson, "Trap Sheets of the Lake Nipigon Basin," *Bull. Geol. Soc. Am.*, XX, 207–9.

[2] Whitman Cross and Ernest Howe, *U. S. Geol. Surv., Geol. Atlas,* Silverton Folio, p. 25; S. R. Capps, "Rock Glaciers in Alaska," *Jour. Geol.*, XVIII, 359–75.

[3] A. C. Ramsay and James Geikie, *Quar. Jour. Geol. Soc. London,* XXXIV, 505–41, 1878.

A matter perhaps less satisfactorily explained is the frequent brecciated aspect of the undisplaced limestone of the Rock of Gibraltar. In the words of the authors cited, "In many places the Rock looks as if it had been smashed up *in situ*, the broken fragments having been subsequently consolidated by infiltration." The authors prove that the shattering is not due to faulting, and attribute it to frost. The fractures recall, however, those of the country rock of the landslide area of the Rico Mountains, referred by Cross[2] to prehistoric earthquakes of exceptional violence. Indeed, the features of the Gibraltar breccias as described by Ramsay and Geikie are not inconsistent with an origin in landslides, which also move out over gentle slopes and carry large fragments to the outer limits.

Landslide breccia.—Breccias of this class owe fragmentation in large measure, and assemblage wholly, to the force of gravity. In *rock-falls* the movement is sudden and violent, and the rock is shattered to pieces by successive impacts. Rock-fall breccia is a chaotic mixture of blocks, large and small, set at all angles and sharply angular. In the few seconds of the tremendous downrush of perhaps millions of tons of rock, the fracture of the masses to smaller and still smaller fragments and their crush to powder go on so rapidly that comparatively little opportunity seems to be given to the rounding of edges by attrition. The matrix consists of chinkstone and pulverized material and may embrace a contribution of soils and subsoils swept up by the rock-torrent.

Large rock-falls on steep slopes obtain sufficient momentum to carry them a considerable distance over gentle and even reversed gradients at the mountain's base. In the Elm rock-fall of 1881 the landslide mass, after reaching the foot of the mountain, poured down the level valley floor for nearly a mile, covering it over its whole width to a depth of more than 30 feet.[1] The section of a rock-fall breccia taken normal to the cliff therefore resembles that of the rock-glacier. No marked difference in the size of fragments in different parts of the area covered has been recorded, so far as the writer is aware. In the breccia formed by the landslide at Frank, Canada, in 1903, described by McConnell and Brock,[2] large rocks are said to be common everywhere.

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[1] James Geikie, *Prehistoric Europe* (London, 1881), p. 219.

[2] Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

In rock-fall breccias, fragments are of local derivation and of a limited number of kinds of rock. No zonal arrangement is possible in a single slide; but where repeated falls occur, the earlier bringing down material from higher horizons on the mountain and the later falls material from lower terranes, zonal arrangements both vertical and horizontal may result. Thus Howe[3] explains the zone of rhyolite which forms the outer rim of the Pierson Basin rock-stream in Colorado, while the center of the mass consists of fragments of andesite of a lower volcanic series.

In *rock-slides* the movement is gradual and repeated. The displaced mass, therefore, is not so completely broken up as in the rock-fall, nor does it come to cover so large an area, except under special conditions. No type of breccia contains such large blocks as this. While the largest blocks of the Frank rock-fall measured 40 feet, blocks 300 feet in diameter occur in the Rico rock-slides, and in the profounder displacements of the adjacent telluride quadrangle one block of more than two miles in length has been described.[4] On the north side of the Grande Ronde River, Idaho, the Columbian lavas supply slidden blocks half a mile in length.[5] The breccia of rock-slides is characterized by the confused relations of the slipped blocks, their varying dip and strike, their fissured and shattered condition, and their merging in places into rubble breccia of small fragments due to the breaking up of the blocks either by the force of the original slide or by that of later movements. A diagnostic may be found in the inward dip of the blocks, as noted by Russell.[1] Owing apparently to friction with the surface, the sliding blocks tend to rotate backward on axes normal to the slope and thus come to rest with a marked dip toward the cliffs from which they were derived. On the other hand, blocks creeping down talus maintain a dip parallel with the slope. The upper surface of both rock-fall and rock-slide breccias is hummocky, but this feature will hardly be preserved excepting where the landslide fell into deep water.

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[1] Sir W. M. Conway, *The Alps from End to End* (Westminster, 1895), 3d ed., p. 246.

[2] R. G. McConnell and R. W. Brock, *Ann. Rept. Dept. of the Interior, Canada*, 1903, Part VIII.

[3] Ernest Howe, "Landslides in the San Juan Mountains, Colorado," *U.S. Geol. Surv., Prof. Paper 67*, p. 34.

[4] Whitman Cross, *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 146.

[5] I. C. Russell, *U.S. Geol. Surv., Water Supply Paper 53*, p. 76.

Bajada breccia.—The rugged mountains of arid regions are commonly fringed with wide slopes of rock-waste called bajada. Like those of talus, the fragments of the bajada have been detached by mechanical weathering. But unlike other subaërial breccias, the bajada has been aggregated largely by intermittent streams. Its fragments have been more or less water-worn. It forms an imperfect breccia and yet is far from being a typical conglomerate of well-rounded pebbles. The streams which build the bajada have certain peculiarities which greatly lessen the wear on the stones they carry. The long accumulated waste on the mountain slopes swept down by spasmodic rains loads so heavily the temporary streams of the barrancas that they have been designated as mud-flows.[2] In the washes and on the lower unchanneled slopes of the bajada the viscosity of the flow is further increased by absorption of the water by the thirsty sands. In the moving mass of the mud-flow, stones such as are carried in mountain torrents of humid climates as the bottom load and dashed against one another and the stream bed are here intermingled with the finer waste held in suspension, and are thus protected from mutual abrasion. Hence pebbles remain imperfectly rounded even to the outer edge of the bajada slope.[3]

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[1] I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," *U.S. Geol. Surv., 20th Ann. Rept.*, Part II, p. 19.

[2] For a graphic description of a mud-flow in the Himalayas see Sir W. M. Conway, *Geog. Jour.*, II (1893), 291.

[3] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 469.

Unlike all other subaërial breccias, the bajada is stratified, and unlike that of marine and ordinary fluviatile conglomerates, the stratification is imperfect. The bedding is often local and ill-defined. Unsorted beds pass both vertically and horizontally into those well sorted. All this follows from the nature of the building-streams. Leaving the barrancas of the mountains and debouching on the gentler slopes, they suffer a sudden arrest of velocity as well as diminution of volume by the absorption of their waters. These checks are often enough to cause them to throw down their load, fine and coarse alike, with little or no sorting. The attitude of unequiaxed fragments of mud-flows on bajadas has not been sufficiently observed. It may be inferred from the method of their carriage that they will not always take the position of repose and that even flat stones may be left at any angle.

A bajada breccia is wedge-shaped, but on a larger scale than that of talus. Furthermore, there is a gradual decrease in size and angularity of the material in passing from the thick to the thin end.

The matrix of the bajada consists of the finer stream-wash and of dust and sand contributed by the wind. Beds of rubble breccia with interstitial matrix pass into endostratic breccias of predominant matrix and sporadic fragments. A characteristic matrix is a chemical deposit of lime carbonate by calcareous evaporating water. As in the Tintic mining district, Utah,[1] the material may thus be cemented into compact rock in which roofs and walls of deserted tunnels remain standing for years untimbered. The limy matrix may whitewash the pebbles and, by filling the interstices, form beds of caliche.

Dry climate conditions are indicated further by the absence of carbonaceous deposits and by the complete oxidation of iron compounds, the interfingering of playa clays about the outer margin, and, under extreme aridity, the association of beds of salt and gypsum in the centers of the bolsons. Wind-carved pebbles may be found, and beds of the millet-seed sand of the desert. The presence of well-rounded sand grains in a breccia, however, is a criterion to be used with intelligent caution. Desert sand once shaped retains its form indefinitely. Thus the St. Peter sandstone, whose grains were originally ground under desert winds, was spread by the Ordovician sea, and again supplied the material for the Sylvania sandstone of Michigan. Either of these sandstones could furnish desert sand to breccias of several different types.

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[1] G. W. Tower and G. O. Smith, *U.S. Geol. Surv.*, *19th Ann. Rept.*, Part III, pp. 668–69.

Bajada breccia is of local derivation; far-traveled stones from distant sources are not expected, yet the extent and complexity of the feeding-mountains may give the breccia great lithological heterogeneity. Ancient breccias are not necessarily associated with the buried mountains or uplands which supplied their waste. Such elevations may have been destroyed in the building of the bajada or by later denudation.

The Permian breccias of the Midlands, England, are now commonly regarded as of bajada origin.[1] They occur in rudely stratified, wedge-shaped masses, some more than 200 feet thick at one end and thinning out within four to eight miles. Beds of breccia are interstratified with current-laid sandstone and with marl, into which they graduate both vertically and horizontally. The fragments embrace a large variety of rocks and are now considered of local derivation. They are angular and subangular, more or less water-worn, but are never well rounded. Half a foot is a common measure of their size where they are largest. The matrix is calcareous or sandy.

Certain coarse breccias, intercalated with thin sandstone layers, in the Esmeralda formation of Nevada have been classified as detrital-slope breccias by Turner.[2] Examples well known to American students are the bajada breccias of the Newark formation.

Glacial breccia.—Subaërial glacier deposits are certainly to be classified as breccia, but their characteristics are so well known and so easily recognized, as a rule, that no description is considered needful.

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[1] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 463–70; W. W. King, *ibid.*, LV (1899), 97–128; T. G. Bonney, *ibid.*, LVIII (1902), 185–203.

[2] H. W. Turner, "Geology of Silver Peak Quadrangle," *Bull. Geol. Soc. Am.*, XX, 245.

Volcanic subaërial breccia.—Volcanic breccias laid in open air include:

1. Flow breccia, in which unrounded fragments have become incorporated in flowing lava, either from its frozen and broken crust or from material, volcanic, residual, or of other origin, overridden by the advancing stream.

2. Tuff breccia, made up of the fragmental products of explosive eruptions. The matrix consists of the finer materials of the eruption and in some instances has been washed in by mud-flows. Or the matrix may be formed by gangue and ore stuffs deposited in the interstices by heated waters. Tuff breccias often include fragments of the country rock torn from the sides of the duct below the base of the volcanic cone.

Subaqueous breccias.—Breccias accumulated under water may be divided into three general classes with the following subdivisions:

1. Breccias of subaërial fragmentation
   - *a*) and *b*) Subaqueous talus and landslide breccia
   - *c*) Raft breccia, deposits from rafts of ice (iceberg or ice floe), trees, or seaweed.
   - *d*) Desiccation breccia
   - *e*) Subaqueous volcanic breccia
2. Breccias whose fragmentation is the work of aqueous agencies or of agencies working in water
   - *a*) Shoal breccia
   - *b*) Reef breccia
   - *c*) Beach breccia
   - *d*) Tide-glacier and shore-ice breccias
3. Breccia whose fragmentation is due to internal stresses
   - *a*) Glide breccia due to overload, earthquakes, deformation, undercut

Talus and landslide subaqueous breccias.—These two varieties may be taken up together because of certain common features. Both consist of local beds of angular fragments from near-by sources, intercalated between younger sedimentary strata. Suitable topographic conditions for the formation of each are found in the fjords and rias of a rugged coast and in mountain lakes, especially Chelans, lying in oversteepened glacier troughs. The matrix is partly of the same material as the fragments and partly of infiltrating sediments. It is generally interstitial, in contrast with the preponderant matrix of raft breccias, but about the margins blocks projected farthest may be found sporadic.

Talus and landslide breccias may be discriminated from each other by their characteristic profiles—the even and smooth slope talus and the hummocky surface of the landslide—by the longer extension of the landslide from the parent cliffs, and, in the following example, by the landslide tearing up the sediments of the sea-floor over which it moves and mingling them with its own débris.

The very interesting Jurassic breccia of the Ord, on Moray Firth, Scotland, is pretty certainly due to a landslide fallen into the sea.[1] The strata among which the breccias are imbedded consist of finely laminated shales with occasional thin seams of limestone. Hence the water in which they were laid was quiet, unvexed by powerful waves or currents. The littoral fossils—ammonites, corals, etc.—show that the deposits are marine and indicate the close proximity of the shore. This is confirmed by numerous remains of cycads, ferns, and conifers apparently drifted in by rivers. Both fauna and flora prove the warmth of the climate and forbid the assumption of an ice raft as the means of transportation. The breccia is contemporaneous with the Jurassic beds in which it lies, but it is not intraformational, since its fragmental material is derived from the Old Red Sandstone which occurs in the immediate vicinity. The fragments vary in size from chipstone to blocks 10 feet in diameter. The majority are sharply angular, some show signs of attrition on the edges, and not a few, especially those of smaller size, are completely rounded. They are heaped together in the wildest confusion. The upper surface of the breccia beds is irregular, and the strata deposited upon it show the influence of its projections. The breccias vary in thickness from a foot or two to 50 feet. The matrix is fossiliferous with contemporaneous Jurassic fossils in a more or less comminuted condition. In places are found numerous masses of Jurassic reef-building coral torn from their bases and heaped in all positions among the débris.

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[1] J. W. Judd, "The Secondary Rocks of Scotland," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 187–95; J. F. Blake, "On a Remarkable Inlier among the Jurassic Rocks of Sutherland," *ibid.*, LVIII (1902), 290–310.

All these phenomena are explained by landslides descending from the steep slopes of Old Red Sandstone hills or mountains into the quiet waters of a Jurassic fjord or ria and depositing on the even-layered silts the tumultuous beds of breccia. The débacle would sweep up rounded pebbles from the beaches, tear corals from their bases, crush shell banks in the estuary, and mingle their débris with the fragments of the slides. That earthquakes were the cause of these great rock-falls is suggested by the contemporary sandstone dikes found in the district.[1]

It may be added, if only in illustration of the diverse interpretations held of breccias, that Murchison[2] described these breccias as due to crush incident to the upheaval of neighboring granite. Blake[3] argues the deposit of an ice foot. Huddleson, in the discussion of Blake's paper, postulates ocean currents strong enough to tear up masses of corals and to gather and distribute old shore accumulation of talus, although ocean currents, even if powerful enough to transport the immense blocks of the breccia without wear of edges, are not so paroxysmal as to heap them in the midst of the fine silts of quiet water. Judd[4] recognizes the cataclysmic nature of the formation and suggests very tentatively river-floods of the most violent character. Yet the floods of a river cannot be expected so to maintain their energy on entering the ocean as to deposit their bottom load in water of considerable depth and to mingle it with detritus torn from the ocean floor. The momentum of the rock-fall would seem to be the only force capable of the work, and this origin is advanced by Woodward[5] and by Teall[6] in the discussion of Blake's paper.

Raft breccias.—In breccias of this class the fragments have been transported in such a way as to escape wear *en route*. Angular fragments of such soft rocks as shale and talcose, schists and limestone, brought unworn from distant sources, prove that the carriage was upon the surface of the ocean, and not by wave and current along the ocean floor. Further evidence of surface transport should be looked for in disturbances in the bedding of the inclosing strata. Laminae beneath the larger stones may be bent down, and the succeeding laminae may show the influence of the projecting blocks, thus proving that the fragments were dropped through some depth of water. Confirmation has been found in the position of fragments with the heavier ends downward.

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[1] H. B. Woodward, *Quar. Jour. Geol. Soc. London*, LVIII (1902), 206.

[2] *Transactions Geol. Soc. London*, Ser. 2, Vol. II, Part II, p. 293.

[3] *Op. cit.* [4] *Op. cit.* [5] *Op. cit.*

[6] *Quar. Jour. Geol. Soc. London*, LVIII (1902), 205.

Raft breccias are endostratic and the fragments are sporadic. There may also be an irregular distribution of them—in places a huddle of fragments where the unloading of the raft was sudden. Some blocks may be quite too large for wave and current carriage.

Rafts capable of transporting the material of breccias are either of ice or of vegetation. Ice rafts include both icebergs and shore ice in the form of floes, or of the ice-foot.

Iceberg breccia.—Since the iceberg is detached from the tide glacier, iceberg breccia is composed of the material of the ground moraine. In a larger or smaller proportion the fragments prove their derivation by their subangular form and striated faces. A considerable lithologic variety is to be expected, since the parent glaciers usually drain a large extent of country. Transport from distant sources has long been looked upon as evidence of iceberg carriage, since icebergs drift farther than other rafts.

In weighing the evidence of iceberg breccia, and of glacier breccia as well, it is often necessary to discriminate glaciation of pebbles from slickensides by earth movements which affect the mass of the formation. In favor of glaciation is the incrustation of planed or striated surfaces by marine organisms, such as serpula or shells, since these surfaces must have been produced before the deposit of the pebbles in the breccia beds.[1]

Striae may be considered "rutsch striae" produced after the deposit of the breccia under the following conditions: (1) when they occur on matrix as well as pebbles; (2) when they are found on different planes below the surface of the pebbles; (3) when they affect traceable planes or zones of shear; (4) when the striae of different pebbles in the same plane run in the same direction and correspond in direction with earth movements recorded in adjacent strata; (5) when the number of striated pebbles in different parts of the breccia varies directly with the amount of shear; (6) when the striae on faulted pebbles end at the fault plane; (7) when the striated surface is covered with films deposited from solution. Several of these diagnostics are mentioned by Marr[1] as characteristic of scored pebbles having the form of glacial bowlders in an English breccia. Tectonic breccias often display slickensided blocks,[2] but they are hardly liable to be confounded with glaciated pebbles. It may be added that the proportion of glaciated pebbles in iceberg breccias may be exceedingly small in comparison with that in the drift-sheets of far-traveled continental glaciers.

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[1] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, p. 25; W. J. Sollas and A. J. Jukes, "Included Fragments of the Cambridge Upper Greensand," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 11–15.

Iceberg breccia, as well as any other, may be sheared after its formation. In this case neither slickensides nor glaciation can be used to disprove the other process. A dual origin seems to be indicated in scored pebbles of some of the Permian breccias of England, but there are students who claim that they are due to earth movements only.

Shore-ice breccias.—In arctic regions shore ice often receives a load of angular waste, and, drifting along the coast or out to sea, desposits it as breccia amid the sediments of the ocean bed.

The ice-foot, described by Feilden and De Rance[3] as having its origin chiefly in snows drifted into water offshore, receives the waste of the talus slopes at whose base it lies. Ice floes along shore also obtain a load of similar débris tobogganing out from talus slopes and falling upon the floes from sea-cliffs. Shore ice may also carry rounded beach pebbles frozen to its base and glaciated pebbles shaped by the grinding of ice pans on shelving shores in storms and under the action of the tide.

The Quebec group of the Ordovician of Canada contains breccias explained by Sir J. William Dawson as early as 1833 as due to shore ice.[1] These breccias are very irregular in their distribution and vary rapidly and greatly in their thickness. The fragments are of Cambrian limestone and of the lower limestones of the Quebec group. "The only means of explaining these conglomerates seems to be the action of coast ice . . . . which seems to have had great reefs of limestone, probably in the area of the Gulf of St. Lawrence, to act upon and to remove in large slabs and bowlders, piling these up on banks to constitute masses of conglomerate." Walcott also postulates floating ice in the absence of any other explanation in accounting for bowlders in certain intraformational conglomerates, saying: "No other explanation occurs to me that will account for the transportation of a bowlder from the shore line and the placing of it upon the sea-bed so as not to disturb to any marked degree the sediments then accumulating."[2]

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[1] J. E. Marr, "Notes on a Conglomerate near Melmerby," *Quar. Jour. Geol. Soc. London*, LV (1899), 11–13.

[2] E.g., the Wapsipinicon breccias of Iowa, W. H. Norton, *Iowa Geol. Surv.*, IX, 447–48.

[3] H. W. Feilden and C. E. de Rance, "Geology of the Arctic Coasts," *Quar. Jour. Geol. Soc. London*, XXXIV (1878), 563–66.

The bowlder beds of the Talchir group of India are attributed to ice rafts by Oldham.[3] Sporadic bowlders from distant sources and reaching a maximum diameter of 15 feet are distributed with extreme irregularity in distinctly stratified shales and sandstones. Large numbers occur within limited tracts, but over many square miles of the area they are quite absent. Where the sedimentary matrix is laminated, the laminae bend down beneath and arch over the included blocks. As the fragments are far too abundant and widespread to have been carried by rafts of vegetation, floating ice remains the only possible vehicle. This inference is confirmed by the presence in two localities of striated pebbles, although most of the fragments are distinctly water-worn. The various phenomena of the Talchir beds point to their accumulation in large inland water bodies covered with ice in winter, to which torrential streams led down steep valleys and to which glaciers locally descended.

Tree-raft breccia.—Uprooted trees, drifted down to sea on river-floods, may carry for some distance out from shore angular stones of the waste mantle and of the weather-broken rocks beneath, firmly held entangled in the meshes of their roots. The fragments may be expected to be smaller than those of the ice raft. Fine waste is absent from the breccia, since it is soon washed out of the interlacing roots of trees when immersed in river or sea. Since the fragments are derived from the zone of weathering, decomposed and etched surfaces and weather-rounded edges may be looked for, especially in fragments made of the more soluble rocks.

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[1] Sir J. W. Dawson, "On the Eozoic and Paleozoic Rocks of the Atlantic Coast of Canada," *Quar. Jour. Geol. Soc. London*, XLIV (1888), 809–910, quoting an earlier paper.

[2] C. D. Walcott, "Intraformational Conglomerates," *Bull. Geol. Soc. Am.*, V, 197.

[3] R. D. Oldham, *Geology of India*, 2d ed., pp. 157–60.

Seaweed breccia.—The buoyant power of seaweeds and the tenacity with which they adhere to rock are well known. They are thus able to transport stones so small that they would readily escape from the roots of floating trees. At the Orme's Head, North Wales, angular fragments of limestone have been found attached to the roots of Laminaria.[1] The stones which seaweed commonly carry are the well-worn shingle of the pebble beach. But angular stones may be transported by them when fragments are broken by the battering of waves from the rocky reefs on which seaweeds grow.

A pudding breccia occurring in one or two localities near Dublin, Ireland, has been attributed to tree rafts by Jukes[2] and to carriage by seaweed by Ball,[3] although earlier observers had invoked rafts of floating ice. The matrix is highly fossiliferous, encrinital, carboniferous limestone. The fragments, sharp-edged, sporadic, small, are of granite and metamorphic rock outcropping in the neighborhood. The small size of the fragments lends some weight to seaweed as the transporting agent.

Desiccation breccia.[4]—Surface layers of unconsolidated fine-grained sediments, such as clay or limy mud, when exposed to the air, dry, shrink, and sun-crack. The angular blocks of this mosaic may again be covered with water and imbedded in the sediments which it throws down. The conditions for desiccation breccia are afforded where there are long intervals between periodic floodings, as in the shallow lakes of arid basins and those of river flood-plains and in lagoons cut off from sea except at highest tide or greatest storms. Desiccation breccia may be only as thick as the sun-cracked layer. Where the dried blocks of the mosaic or pieces of their upturned edges are assembled by the waves, the fragments may be irregularly piled in rubble and should show some wear. The matrix differs little from the fragments, and the breccia is endostratic. A special variety is playa breccia. The cracks of the sun-baked clay of the dried-up lake bed may be filled with desert sand, and this accumulates also beneath the curled-up edges of the cakes. Desiccation breccias have been described from the Algonkian of Idaho by Ransome and Calkins,[1] and designated as "mud breccias." The angular or slightly rounded fragments are of argillite and are imbedded in a somewhat coarser-grained and more arenaceous matrix. Sun-cracks are found in direct connection, and the angular fragments are supposed to be broken off from the edges of flakes of mud curled up by drying in the sun.

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[1] C. E. de Rance, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 374.

[2] Jukes, *Manual of Geology* (1886), p. 298.

[3] V. Ball, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 371–74.

[4] Desiccation conglomerates is a term proposed by J. E. Hyde, *Amer. Jour. Sci.*, 4th ser., XXV, 400 f.

Volcanic subaqueous breccia.—Volcanic breccia deposited under water may be distinguished from that laid on land by the sediments on which it rests and by the bedding of the tuff. Subaqueous tuff breccias, as remarked by Leith,[2] are distinguished only with very great difficulty from water-laid clastics resulting from the erosion of volcanic rocks.

Shoal breccia.—In this class of submarine breccias, and in reef and beach breccias as well, disruption and assemblage both are caused by waves and tides. The normal action of these agents is to round and sort the coarser stuff they handle and to deposit it in well-defined conglomerates. It is only under exceptional conditions that they can assemble beds of fragments so little worn as to constitute a breccia.

Shoal breccia is formed by the action of waves and tides on shoals due to diastrophic movements or to general aggradation. In reef breccia, on the other hand, there is proof that the shallows permitting wave-pluck are due to local upbuilding of the sea-floor.

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[1] F. L. Ransome and F. G. Calkins, "Geology and Ore Deposits of the Cœur d'Alene District, Idaho," *U.S. Geol. Surv., Prof. Paper 62*, p. 31.

[2] C. K. Leith, *Structural Geology* (New York, 1913), p. 66.

Shoal breccias are commonly of limestone. Calcareous sediments rapidly harden by cementation, and may be broken into breccia by waves which under identical conditions merely redistribute the grains and particles of unindurated sands and clays. On shoals of calcareous sediments lying partly above and partly below the plane of effective wave-erosion, waves and tides tear up the cemented beds of the elevations and deposit fragments in the hollows safe from further wear.

In the case of the extensive sheets of brecciated limestone of the Galena and the Niagara formations of Wisconsin, Chamberlin[1] has suggested that the tide may have played an important rôle. Under a large tidal oscillation storm waves may be brought at low tide within reach of the surface of shoals which, except at this brief interval, remains below wave-base. Fragments torn at low tide by storm waves, and the finer waste stirred into suspension, thus have time to settle back together as fragments and matrix of a breccia, and, it may be added, to be further protected by a cover of other sediments before a low tide again coincides with a heavy storm and the process is repeated.

Strong tides working on shoals are postulated by Lane[2] in explaining the limestone breccias of the Salina and Lower Helderberg of Ohio. The prevalence of ripple-marks, mud-cracks, brecciated and conglomeratic layers, leads to the inference of a great flat which seems to have been just awash. "If we imagine tides like those of the Bay of Fundy rushing over this flat, producing this breccia and conglomerate . . . . we have the conditions of the Helderberg on Monroe deposits."

In explaining the foundations of Mississippian reefs in Yorkshire, England, Tiddeman[3] infers local deformations which here and there brought the sea-floor above wave-base. As a result, shoals were formed of wave-plucked angular and more or less rounded fragments on which colonizing corals and mollusks reared their reefs. In a similar way certain Algonkian breccias of Idaho are explained by Ransome and Calkins.[4] "It is supposed that in the vast mud flats upon which the St. Regis beds were being laid down, the surface was raised up into a low dome of small extent upon which the soft strata were exposed to wave action and fragments were broken away and incorporated with the soft siliceous mud that was then accumulating in the surrounding waters."

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[1] T. C. Chamberlin, *Geology of Wisconsin*, I (1883), 168–69.

[2] A. C. Lane, *Geol. Surv. of Michigan*, V (1895), Part II, p. 27.

[3] R. H. Tiddeman, cited by Marr, *Quar. Jour. Geol. Soc. London*, LV (1899), 330.

[4] *Op. cit.*, p. 38.

Reef breccia.—Reefs with brecciform structures may be built by corals, calcareous algae, and molluscous shells. Coral breccia, the variety most common and most closely studied, is produced in several different ways. As a coral reef is built up toward low-tide level, the interspaces between the masses of growing coral are filled with broken fragments of coral branches and the finer waste of the reef. The coral framework is brittle and is further weakened by boring worms and mollusks; hence the accretion of broken branches goes on below the zone of wave-wear, and the fragments remain angular. After wave-base is reached, accretion proceeds still more rapidly, and now the other rim of the reef, the belt of its most active growth, acts as breakwater and protects the inner portions of the coral fields from the wear of the surf. Thus is formed *reef-rock breccia* or coralline rag, a well-cemented limestone in which masses of coral retain the attitude and position of growth, and to which the varied animal and vegetal life of the reef contributes.

In this reef-rock waves cut the channeled and cavernous rock-bench. The fragments plucked from the bench are swept inland by heavy storms over and beyond the beach of coral sand, and cover large tracts with lichen-blackened fragments, angular to such a degree that both Dana[1] and Sollas[2] have compared them to the rough clinkers of lava which strew the slopes of Mauna Loa and of Etna. Intermixed is wave-worn and wind-blown coral sand, which acts as a matrix, cementing the *breccia of the island rock.* By slow subsidence these deposits may be carried beneath the surface of the sea. The upgrowth of the rim of the reef meanwhile protects them from being worked over by the waves and thus the brecciated stucture is preserved.

A third variety of coral breccia accumulates at the foot of the steep outer face of the reef, where angular fragments torn by waves from the growing corals of the rim come to rest below wave-base. Such a breccia, at the foot of reefs of Mississippian limestones in Great Britian, has been described by Tiddeman.[1]

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[1] J. P. Dana, *Corals and Coral Islands* (New York, 1879), p. 178.

[2] W. J. Sollas, *Age of the Earth* (London, 1905), chapter on Funafuti, p. 108.

The characteristics of coral breccia may be enumerated:

1. Like all wave and tide breccias, coral breccia is either a rubble or a pudding breccia. Crackle and mosiac breccias are not to be expected.

2. The matrix consists of the fine detritus of the reef.

3. Both matrix and fragments are singularly devoid of siliceous and argillaceous impurities. An exception occurs in reefs which receive more or less waste from an adjacent land.

4. Reef-rock breccia may show little or no trace of bedding. In the core of the deep boring of the Funafuti atoll, which passes through this rock to a depth of 1,114 feet, the only stratification found was that due to such irregular accumulation of detrital material as occurs between and around the corals.[2] The numerous Silurian reefs of Wisconsin and Iowa show little or no trace of bedding from top to bottom, while areas occur within them of conglomeratic or brecciated structure.[3] In the case of the wave-driven fragments of the island rock some sorting and bedding with low dips are to be expected, and the talus formed below the reef probably shows rude layers dipping outward at the angle of repose.

5. The fragments of coral breccia show varying amounts of wear. Least worn are fragments of reef rock accumulated below wave-base. The island rock necessarily approaches a conglomerate in the rounding of its constitutent masses. How short a time and distance are needed to destroy the angularity of fragments is seen in a photograph and description by Kent[4] of the result of a single tropical hurricane of a few hours' duration in 1884. A fringing reef was wrecked and its fragments, swept inland, were piled above reach of the highest tides. Massive head-corals were torn up and rolled together like the small pebbles of the beach and ground down to subspherical symmetry.

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[1] R. H. Tiddeman, *Rept. British Soc.* (Newcastle-on-Tyne), p. 602.

[2] Judd, quoted by Sollas, *op. cit.*, p. 128.

[3] T. C. Chamberlin, *Geology of Wisconsin*, I, 184; W. H. Norton, *Iowa Geol. Surv.*, IX, 424; XI, 307.

[4] Saville Kent, *Great Barrier Reef of Australia*, pp. 50–52.

6. Coral breccia is intimately associated with stratified deposits of coral mud and sand and pebbles. The reef contains stretches of barren sand within the outer rim. The island is bordered by a beach of sand and shows extensive tracts of sand in the interior. Soundings disclose belts of sand with which the talus of the reef must interfinger. Fine-grained limestones are forming in the lagoon and in deeper offshore waters.

7. Fragments may themselves be brecciform. Complex brecciation occurs especially where fragments of the reef-rock breccia are carried inland to form the island rock.

8. The chief diagnostic of an ancient coral breccia is the presence of the reef proved to be the work of corals by its fossils. Thus the classification of the breccia of the St. Louis formation of southeastern Iowa and adjacent parts of Missouri and Illinois as a coral breccia is held untenable by Bain[1] because of the absence of reef-building corals. On the other hand, brecciated structures connected with coral reefs are not necessarily of coral origin. Associated with the Silurian reefs of Iowa are local breccias unquestionably due to the later deformation of beds of limestone accumulated upon the flanks of the coral mounds.

Beach breccia.—On beaches where wave-action is inefficient and angular blocks are supplied as from sea-cliffs, a deposit of fragments so little worn as to be classed as breccia according to prevailing usage may result under conditions of rapid submergence. In all cases, however, more or less wave-wear will be found upon the fragments, and the deposits, like other subaqueous deposits of both angular and rounded material, should perhaps be termed a breccia-conglomerate.

The St. Louis breccia of southeastern Iowa, classified by Gordon[2] as reef breccia, is considered by Bain[3] a shore formation in which blocks of limestone up to 4 feet in diameter were torn from their beds and buried in sands apparently at the foot of a series of cliffs. Savage[4] also finds evidence of vigorous wave-action and a close proximity of the shore. The subaqueous origin of the breccia is confirmed by Van Tuyl,[1] but only in part. The first period of disturbance was one in which, under violent wave-action, mounds of shoal breccia were produced. The major disturbances, however, are of later date and gave rise to tectonic breccias associated with mashing, folds, and overthrust faults.

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[1] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[2] C. H. Gordon, "On the Brecciated Character of the St. Louis Limestone," *Am. Naturalist*, XXIV (1890), 305–13; *Jour. Geol.*, III, 289 f.

[3] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[4] T. E. Savage, *Iowa Geol. Surv.*, XII, 263 f.

Tide-glacier breccia.—Tide glaciers, laying their loads on sea-bottom, give rise to breccias which prove their parentage by faceted and scored pebbles of a considerable variety of rocks and by subjacent disturbed sedimentary deposits or glacier pavements where the ice has overridden the sea-floor. Associated stratified beds with littoral fossils prove the breccia submarine. Icebergs detached from the glacier front extend the formation seaward in an ice-raft breccia, with a lessening proportion of morainal stuff.

The Chaix Hills, described by Russell,[2] are carved from an uptilted block 4,000 or 5,000 feet thick, composed of morainal material and sea-clays. The fragments of this breccia are sporadic throughout the terrane from base to summit. They are both angular and rounded and reach a diameter of some 8 feet. Lithologically they are as various as are the bowlders of the moraines of the living glaciers of the encircling mountains. Sea-shells of living species are numerous in the finer portions, which are largely made of glacier silts.

Glide breccias.—The sediments of the sea-floor are subject to slow and rapid gravitational movements, comprehensively termed glides, which deform, shatter, and brecciate the involved strata. Glides may be expected to affect the steeper slopes, such as the sides of submarine channels, the front of deltas, and the edges of continental shelves. They are known to have taken place on slopes as low as about three degrees. The mobility of marine deposits is increased by permanent saturation and frequently by lack of cementation.

Subaqueous glides may be classified according to their chief precipitory causes as *overload* glides, *earthquake* glides, and *deformation* glides.

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[1] F. M. Van Tuyl, "Brecciation Effects in the St. Louis Limestone," *Bull. Geol. Soc. Am.*, XXVII, 122–24.

[2] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, pp. 24–26.

Overload glides: On land, gravitational movements occur on slopes due chiefly to erosion; on the sea-floor unstable equilibrium must often result from aggradation. Sediments are unequally spread owing to set of current and distance from sources of supply. Deltas and banks are thus built up, until along their edges overload gives rise to facial shear and glide.

Earthquake glides: The chief geologic effect of earthquakes on land is to precipitate movements both of the waste mantle and of the solid rock beneath. Alluvium on valley floors lurches toward the thalweg, the waste on hillsides, slumps and avalanches, and even solid rock may be intimately shattered and shaken down in landslides of the first magnitude.[1] The effects of earthquakes on marine deposits must be of similar nature and proportionally great. Evidence collected by Milne[2] proves conclusively the fact of subaqueous glides and their close connection in a number of instances with earthquakes. Since the continental delta throughout geologic time has been the zone, not only of sedimentation, but also of great diastrophic movements of which earthquakes are an expression, it may be assumed that earthquakes have been a not uncommon cause of glides in geologic history. Yet no instance is known to the writer in which a glide breccia has been assigned to this precipitory cause. The most direct evidence pointing to such an origin is to be found in contemporaneous associated faults or sandstone dikes. Since earthquakes recur in the same area for long periods of time, earthquake-glide breccias may recur at successive horizons in a formation on in a sequence of formations.

Deformation glides: There is some reason to believe that within the continental delta deformation may so accent the slope that glides of unindurated sediments result. In explaining the Devonian breccia of Iowa, McGee[3] offered as "a useful even though a far-fetched hypothesis" that of an elevation at the close of the Devonian by which the declivity was increased, a consequent slight

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The California Earthquake of April 18, 1906, I, Part II, pp. 384 f. (Carnegie Institute, 1908); Darwin, *Voyage of a Naturalist* (London, 1891), p. 220; Whymper, *Travels amongst the Great Andes*, IV (London, 1892), 260; Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

[2] John Milne, "Suboceanic Changes," *Geog. Jour.*, X, 129–46, 259–85.

[3] W. J. McGee, "Pleistocene History of Northeastern Iowa," *U.S. Geol. Surv., 11th Ann. Rept.*, p. 323.

settling seaward of the fresh-formed Devonian sediments upon the sloping flanks of the Island of Wisconsin, and a slipping of the strata upon one another causing crumpling, buckling, and brecciation. The same cause is assigned by Hershey[1] for a very local breccia near Galena, Missouri. Minor causes of subaqueous glides are erosion and undercut of submarine banks by springs and currents.

The characteristics of glide breccias are due to the deformation, to the shear and crush of the gravitative movement, and not to its precipitory cause. Hence all the varieties mentioned are alike in structure and have a close resemblance to endolithic breccias caused by deformation.

The fragments are contributed by any layers hard enough to suffer fracture. They may be sharply angular or somewhat worn by mutual attrition. They may be apposed in crackle and mosaic breccias, or disposed in rubble, according to the amount of movement. Fragments may show by their relative positions the initial attitude of the layer before fragmentation. These breccias are likely to graduate into folded structures with parallel and thickened axes and common dips, and the fragments of beds bent before breaking may show flexures and contorted laminae. A zonal arrangement is to be looked for where strata differing lithologically and of a considerable thickness are involved.

The matrix is supplied by the least indurated or most readily comminuted beds, especially by the surface sediments as yet unconsolidated, and by any bottom layer which by its plasticity determines the base plane of the glide. Thus shales furnish matrix to fragments broken from brittle limestones. Matrices evidently pasty and fragments somewhat plastic at time of brecciation point to subaqueous brecciation either by glide or by wave-action, and the former alternative is to be chosen when there are proofs of folding before fracture. This test applies only when brecciation in the zone of flow and fracture is precluded. The relative amount of matrix and fragments is determined by the volumes of strong rock and weak rock involved and by the violence of the movement. Even a breccia of sporadic fragments may result.

[1] O. H. Hershey, "A Devonian Limestone Breccia in Southwestern Missouri," *Science*, N.S., I, 676–78.

Overlying beds are undeformed or share only in later deformations affecting the entire body of the strata. Their contact is accordant where the breccia has been reworked and leveled by wave-action. In this case they contain at bottom fragments of the broken beds, either rounded to a conglomerate or partially angular and forming a pudding or rubble breccia. If the slidden mass is reassembled below wave-base the contact is discordant and superincumbent beds are free from fragments. The breccia may thus be either endostratic or have the hummocky upper surface of a landslide. Glide breccias may graduate laterally as well as vertically into sedimentary beds. They rest on undisturbed strata of earlier date. Endostratic breccias passing within the limits of the same stratum into folded laminae point strongly to an origin in glide. A complete section of a glide and the associated strata would show, according to Heim,[1] the following relations: in the area bared by the glide, (1) a reduction of the number of strata as compared with the adjacent areas, (2) local disconformity without time interval; in the area on which the glided mass came to rest, (3) increase in the number of strata, (4) superposition of older on younger beds, (5) displacement of facies. Glides involving subaqueous and subaërial sediments have occurred in a number of instances on the shores of the Swiss lakes, in Sweden, and along the Black Sea.[2] In the lower Devonian limestones of Gaspe a bed has been described by Logan[3] whose structure is evidently due to subaqueous glide. This bed, 7 feet thick, is made up of several thin layers of limestone and limy shale, wrinkled, contorted, and in places brecciated, while the associated beds are free from marks of deformation.

The edgewise position of broad, flat pebbles in evenly bedded strata near Bellefonte, Pennsylvania, has been attributed by Brown[4] to subaqueous glide.

Endolithic breccias.—Of breccias formed within the lithosphere the following classes may be distinguished: (1) tectonic breccia (dynamic, pressure, friction breccia), due to crustal movements and produced by lateral or vertical pressure or by tension; (2) expansion breccia (caused by increase of volume due to chemical change); (3) founder breccia (ablation, solution breccia), due to the foundering of strata, usually because of the ablation by solution of the supporting beds.

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[1] Quoted by A. W. Grabau, *Principles of Stratigraphy* (New York, 1913), p. 660.

[2] Grabau, *op. cit.*, pp. 657 f., 779 f.

[3] Sir W. Logan, *Geology of Canada* (1863), pp. 391 f.

[4] T. C. Brown, *Jour. Geol.*, XXI, 241–42.

Tectonic breccia.—Three varieties are discriminated: fault breccia, fold breccia, and crush breccia. In the latter, brecciation is accomplished without either faulting or folding except so far as the rupture planes of the breccia may be considered as minute faults.

Fault breccia: Here fragmentation is due either to friction along the fault plane or to distributive ruptures associated with the major fault, and due to shearing stresses. In stratified rock, fault breccias associated with both normal and reversed faults are easily recognized, since the zone of brecciation crosses the planes of bedding. Friction breccias along bedding faults are more difficult to distinguish. Here one must seek for proofs of lateral displacement in slickensides with polish, scorings, and seams of "gouge" (clays formed by grinding). Local breccias of this variety have been identified by Ransome[1] in the Rico Mountains of Colorado.

Complex brecciation is not uncommon, since repeated movements along the fault plane shatter and drag a breccia already formed and firmly cemented with perhaps vein stuff and ore. Breccia zones running parallel with the main fault may show but slight displacement. Thus in the San Francisco district of Utah such breccia zones in brittle quartzite pass downward into monoclinal folds in shale.[2] The rocks on opposite sides of a fault plane may be differently affected—granite, for example, may be sheared and the limestone opposite brecciated.[3] Fault breccias often form aquifers for mineralized waters which deposit matrices of ore and gangue. Many breccias of this class have been brought to notice because of their economic importance.

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[1] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 297.

[2] B. S. Butler, "Geology and Ore Deposits of the San Francisco, etc., Districts, Utah," *U.S. Geol. Surv., Prof. Paper 80*, p. 72.

[3] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," *U.S. Geol. Surv., Prof. Paper 75*, p. 151.

Fold breccia: Under suitable conditions of load and stress beds may fold by means of minor fractures. Cross and parallel fracture planes develop, and under increasing stress the fragments are rotated and displaced. The folded bedding is more or less completely destroyed and there results a mosaic or even a rubble breccia. Where the rock is compressed joints or fissility ruptures are produced. A rising anticline develops radial tension cracks along the convex surface as soon as the deformation passes the limit of elasticity of the rock. In the experiments of Willis[1] the first fractures of the arching strata occurred at points of sharpest curvature—along the axial plane at the summit of the anticline and on radial planes of shear at its base. A basal weak stratum, compelled to rise beneath a competent stratum as the latter was bent upward, accommodated itself to the change by shear, resulting in complete brecciation.[2] Here the breccia occupied the center and base of the anticline, while the competent upper beds remained at first unbroken and later under increased pressure were ruptured by a stretch thrust fault.

The degree of folding necessary for brecciation varies with the rigidity of the stratum, with load, and with the amount and rapidity of application of the stress. Even limestone and granite under slight load yield plastically and bend to a perceptible degree when the stress is very slowly applied.[3] On the other hand, brittle rock under presumably sudden stresses breaks into breccia when the deformation has not exceeded a gentle warping.[4] Under the same strain and load different rocks fold or break according to their elasticity. Among sedimentaries the most brittle and therefore the most liable to brecciate are cherts, some shales, and calcilutites; among metamorphic rocks, quartzites, graywackes, and rather siliceous slates. A thin layer of chert may be seen broken into a string of angular bits within a layer of limestone which shows no other trace of yielding. In the breccias of the Wapsipinicon stage of the Iowa Devonian, a thick, tough, crystalline-granular coquina is normally broken into large slickensided blocks which retain something of the flexures into which the bed was thrown, while subjacent thinly laminated calcilutites are shattered to a jumble of small fragments.[1]

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[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Pls. 75, 76.

[2] *Ibid.*, Pl. 93.

[3] Arthur Winslow, *Am. Jour. Sci.*, 3d ser., XLIII, 133–34; H. F. Bain, *Iowa Geol. Surv.*, VIII, 378.

[4] Smith and Siebenthal, *U.S. Geol. Surv., Geol. Atlas*, Joplin Folio, p. 9.

Shales yield plastically under load, but when near the surface and under sudden stress they easily crush to breccia. Shales promote the fragmentation of inclosing and especially of included beds of other rocks. Thus the Wapsipinicon breccias of Iowa embrace the Independence shale and its associated limestones. In the zone of fracture and flowage, alternate thick layers of brittle and of plastic rock may produce brecciated beds, alternating with folded layers, whose arches may be truncated by the movement of the fragments of the rigid and brecciated beds.[2]

Unlike glide breccias, breccias due to folding are included between strata which have shared the brecciating deformation according to their competency. But since any sort of breccia may be involved along with the associated terranes in a later deformation further proof of origin must be looked for in the remains of initial folded structures in the breccia. A certain continuity may be traced from fragment to fragment, showing clearly that the fragments are constituent parts of a flexed and broken layer. The breccia may graduate into folds. Where the breccia involves beds of different kinds of rocks, anticlines and synclines may sometimes be traced in a zonal arrangement of the crushed material.[3]

Crush breccias: The sheet breccias of the Joplin district, Missouri, illustrate how terranes of brittle rock may be brecciated by lateral pressure without any further mass deformation than that exhibited in gentle warpings. Heavy ledges of chert have been thoroughly and finely crushed in places and cemented by a chemical deposit from ground-water. The fragments are of small size and are thus in direct contrast with the residual breccias of a higher horizon in the same area. The breccia is endostratic and often of the crackle or mosaic type, with fragments rotated but slightly in the ledge.[1]

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[1] W. H. Norton, *Iowa Geol. Surv.*, IV, 158–61.

[2] C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *U.S. Geol Surv., 16th Ann. Rept.*, Part I, p. 681.

[3] W. H. Norton, *Iowa Geol. Surv.*, IV, 165.

In all tectonic breccias the fragments are left of sharpest edge at time of breaking, and a universal sharp angularity points strongly to a tectonic or to other endolithic origin. Yet the fragments may be worn by grinding one upon another in the zone of shear and thus become so completely rounded as to be readily mistaken for the pebbles of a wave-laid conglomerate. Thus are produced the "pseudo-conglomerates" of Van Hise.[2] The rounding of pebbles of a conglomerate, however, is pretty uniform for pebbles of any given size, the smaller being better rounded than the larger. Moreover, the conglomerate graduates into finer sedimentary deposits. The rounding of the fragments of a pseudo-conglomerate is fairly uniform for any given portion of the brecciated zone. Tracts where fragments are well rounded regardless of size pass into tracts where all the fragments are angular.[3] Dale[4] has noted that angular pebbles of soluble rock in an insoluble matrix may be later rounded by the dissolving action of acid ground-water. It may be added that by solution under pressure fragments develop salients and re-entrants, wholly different from either fracture planes or rounding by attrition or solution. Fragments may also show in flexed and contorted laminae evidence of the strain to which their layers were subjected. Such distortion phenomena imply considerable plasticity in the layers, although it was finally exceeded by the strain. Contorted laminae may also be seen in the fragments of breccias originating in subaqueous glides, where the plasticity of the sediment is due to imperfect lithification.

The form and size of the fragments of tectonic breccias so far as due to fracture depend on the amount of stress, the closeness of joints and bedding planes, and the natural fracture of the rock. Thus in one of the experiments of Willis[5] fault planes divided a brecciating layer at first into rhombs bounded by two faults and two bedding planes, and afterward, under increasing pressure, into triangular forms bounded by two faults and one bedding plane. From brittle, thin-layered rocks under slight stresses quadrangular and subquadrangular small fragments are derived. The sharpest edges are found in rocks of conchoidal fracture, minutely faulted into triangular fragments.

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[1] Smith and Siebenthal, *U. S. Geol. Surv.*, *Geol. Atlas*, Joplin Folio, p. 9.

[2] Van Hise, *op. cit.*, p. 679.

[3] *Ibid.*, p. 680.

[4] T. N. Dale, "Structural Details in the Green Mountain Region," *U.S. Geol. Surv.*, *16th Ann. Rept.*, Part I, p. 569.

[5] *Op. cit.*, Pl. 93.

The matrix when contemporaneous is supplied by the material of the weaker beds involved and by wear and tear of the stronger beds. It graduates from powder and angular sand, the product of attrition, to chinkstone, approaching the size of the smaller fragments. When the interstices are left at time of brecciation more or less unfilled, as is likely to be the case, a veinstone matrix of travertine, of jasperoid, or of iron compounds is often deposited later by ground-water. Such a matrix weighs against any origin, e.g., subaqueous glide, which is not likely to leave unfilled interstices. The significance of both veinstone and attrition matrices lies also in the proof they offer that sedimentary deposits had no access to the zone of brecciation.

The material of tectonic breccias, with the exception of the matrix of chemical deposit, derives from the geologic formations of the beds involved. Fragments of beds belonging stratigraphically below the base of the breccia cannot be included in it. On the other hand, in subaqueous or subaërial breccias fragments deriving, for example, from cliffs of Archean rock may be deposited as Devonian breccia on Devonian lands or in Devonian seas. But while in subaërial and subaqueous breccias the matrix is never older than the fragments, in tectonic breccias an older and weaker terrane may supply the attrition matrix, in which the fragments of a younger superjacent stratum are imbedded. Where beds of different rocks are involved zonal arrangement is sometimes traceable, which at once excludes the breccia from many varieties of subaqueous and subaërial origin. A tectonic breccia does not rest, like subaërial breccias, upon an erosion surface. It cannot graduate upward into strata inclosing sporadic fragments. An important diagnostic may be found in undisturbed areas, perhaps of very large size, which have transmitted the strain instead of yielding to it by fragmentation.

Expansion breccia.—Fragmentation may be caused by increase of bulk of the brecciating rock or of associated layers which transmit the pressure to it. Expansion may be caused by recrystallization or by hydration. Expansion breccias graduate into folded structures, but the folds show quaquaversal deformation, the *enterolithic* structure of Grabau,[1] a term translating the "Gekröse" of Koken, and this intestinal coiling may serve to distinguish them and the associated breccias from folds and breccias due to lateral pressure.

Founder breccia.—Where beds of soluble rocks have been in part or whole removed by the chemical action of ground-water, founder breccias of the superincumbent beds are produced on a scale commensurate with the extent of the ablation. All terranes between the dissolving foundation and the surface of the ground or some competent superior stratum are affected by the process. Characteristic features are abnormal dips, sag folds without parallelism of axes, areas of crushed rock alternating with horsts where the strata are undisturbed. The matrix may be of crushed material of the same terrane as the fragments. In this case it is likely to be small in amount and insufficient to cement the breccia firmly, for the attrition of the fragments in founder is probably much less than in tectonic brecciation. The matrix may be a later chemical deposit.

The fragments show only the small wear due to mutual attrition. Like other endolithic breccias, a founder breccia can carry no water-worn pebbles. It is conceived that founder breccias of thick extensive beds include larger blocks than any other type of breccia excepting that due to landslide. Certainly they may be far too great for detachment by waves or by mechanical weathering and for fragmentation under lateral pressure. Horsts may be difficult to discriminate from the undisturbed areas of tectonic breccias.

Thin-shale founder breccias have been described by Ransome[2] in the blankets of several mines in the Rico district, Colorado. The blanket of the Enterprise mine, for example, is an unconsolidated breccia of shale from 2 to 20 feet thick, resting on a thin bed of light-gray earth, shown by chemical analysis to be a residuum of gypsum.

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[1] *Principles of Stratigraphy*, p. 757.

[2] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 273 f.

The Monroe breccia of Michigan is considered by Hindshaw[1] to be of this type, although Lane[2] has classified it as a shoal breccia and Grabau[3] as a rock-stream or rock-glacier breccia, at least in its outcrops at Mackinac Island and the vicinity. As observed by the writer, the breccia at this locality is a rubble, entirely without bedding, of angular fragments set at all angles and varying in size from gravel up to blocks 25 and 30 feet in length. Fragments and matrix are of soft buff magnesian limestone, and the latter is usually interstitial. Occasional seams of calcite and celestite occur. In certain areas a zonal arrangement of material is seen in the prevalence of chert, showing that the material of the breccia has not been intimately mingled as in subaërial breccias whose fragmentation is due to weathering. A still more conclusive negative to such an origin is given in areas of rock quite undisturbed, such as a block extending eastward along the cliffs for upward of 200 feet from the eastern border of the park at Mackinac. This observation is confirmed by Rominger,[4] who states that "frequently large rock-masses composed of a series of successive ledges which have retained their original position to each other are scattered through the breccia." The wide distribution of the breccia in Michigan and Ohio precludes any local origin. The size of the fragments and the absence of water-wear are considered inconsistent with a subaqueous origin. Along the eastern shore of the island, however, numerous talus blocks show endostratic brecciation. Laminae flexed and faulted and partially brecciated are imbedded in a matrix of the same material and maintain more or less of their original parallelism with each other and with the bedding of the stratum. In the undisturbed block at the east of the park at Mackinac sporadic fragments occur toward the base of massive beds. These phenomena imply disturbed sedimentation, or subaqueous glides, at the time of the deposit of the limestone, but the main brecciation is taken to be of later date.

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[1] *Michigan Geol. and Biol. Surv. Publ. 14,* Geol. Ser. 11, pp. 206–7.

[2] A. C. Lane, *Geol. Surv. Michigan,* V, Part II, p. 27.

[3] A. W. Grabau, *Science,* N.S., XXV, 295–96; *Principles of Stratigraphy,* pp. 547–48.

[4] Carl Rominger, *Geol. Surv. Michigan,* I, Part VI, p. 27.

There is also seen an association with folds which suggests either a tectonic or a founder breccia. The underlying red and blue shales seen in the rock bench about the island rise in places as anticlines in the sea-cliffs. On the cliffs east of the fort at Mackinac, beneath a cornice of about 15 feet of horizontal massive beds, appears a zone, 9 feet thick, of thin-bedded limestone, thoroughly crackled, with unhealed seams, shattered, and in places with the fragments rotated and displaced, but with the bedding still traceable to a large extent. In places low folds can be made out with a height of 8 inches and width of some 4 feet, a deformation apparently adequate to brecciate this brittle rock.

The theory of founder presupposes the removal by solution of beds of rock salt and gypsum underlying the red and blue shales on which the limestone rests. These shales are not commingled with the breccia of the limestone. If the breccia is due to founder, it must be concluded that the soft clay shale yielded plastically to unsupported pressure of overlying beds without mixing with the fragments into which these beds were broken. In places small chimneys of breccia penetrate the shales beneath, and the ledges of breccia which rise in reefs above the country rock of shale in the low ground of the north of the island may have a like relation.

The grounds on which Hindshaw's theory of founder is supported are as follows:[1] The Monroe formation rests on the Salina, which includes beds of salt, in places 800 feet in thickness, and of anhydrite partially changed to gypsum. The Monroe itself contains beds of anhydrite. In the Monroe beds and in the overlying Dundee limestone, which is also involved in the brecciation, the circulation of ground-water is exceptionally active. Discordant and abnormal dips occur, accountable for by slumping due to solution of the Salina beds about their outer edges.

Cavern breccia is a local variety of founder breccia. Detached masses fall from the roof and sides of a cave and accumulate on the floor as breccia, which may come to fill nearly the entire space. Cavern breccias may sometimes be recognized by their shape as

[1] *Op. cit.*, pp. 206–7.

casts of the irregular chambers and chimneys of caverns whose walls remain as molds. Cave earth, bone breccia, incorporated fragments of stalactites, and stalagmitic crusts may certify the origin. The matrix is either of travertine or of limestone sand and cave earth.

Campbell[1] has described a cavern breccia exposed in the walls of a canyon near Fort Stanton, New Mexico, and suggests that the frequent repetition of the process might result in complete brecciation of certain beds more soluble than the rocks above and below.

Cavern breccias are common in the lead and zinc mining regions of the Upper Mississippi Valley. Fragments of sheets of ore mingle with the dolomite débris. The matrix may be metalliferous, giving rise to sprangle ores. Slight foundering of the strata above caverns has produced crackle breccias whose fissures are healed with Smithsonite.[2]

Pseudo-brecciation.—This term is used by Wallace[3] to designate irregular mottlings due to partial dolomitization. Various other causes produce irregular mottlings, but such can hardly be mistaken for brecciation structures.

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[1] M. R. Campbell, "Origin of Limestone Breccias," *Science*, N.S., XXVII, 348.

[2] Whitney, *Geology of Iowa*, I, 448; A. C. Leonard, *Iowa Geol Surv.*, VI, 11 f.; S. Calvin and H. F. Bain, *ibid.*, X, 480 f.

[3] R. C. Wallace, *Jour. Geol.*, XXI, 420–21.